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AN INTRODUCTION TO MAGNETOSTRICTIVE DELAY LINES

WHAT IS A DELAY LINE?

The delay line is an extremely versatile device whose basic function is to introduce a time delay in the transmission of an electrical signal. This function is utilized in many ways.

An ideal delay line would perform this function without distorting or altering the information represented by the electrical signal. Therefore, while the signal is in the process of being delayed, the line is said to be holding or "storing" the information -- be it analog or digital.

Since the delay line is no exception to nature's rule that nothing is perfect, electronic amplification is used to compensate for inevitable losses. The combined result? A highly flexible delay or information storage device that is compact, rugged, fast, economical, both in cost and power consumption, reliable, readily reproduced and applicable to a wide variety of useful applications.

This highly desirable delay phenomenon can be achieved either by purely electrical means, as in electromagnetic lines (lumped constant or distributed constant), or by various electromechanical devices grouped under the terms acoustic or ultrasonic delay lines.

Electromagnetic delay lines utilize the fundamental properties of inductance and capacitance, namely that it takes time to charge an inductive-capacitive network and that phase differences between the inductive and capacitive elements result in time delay. This type of delay line is generally limited to short time delays because of the fact that electrical energy propagates at the speed of light.

The ultrasonic delay line converts electrical energy into mechanical energy in the form of acoustic waves, which propagate at a velocity very much slower than electrical energy thereby affording long delay times. The ultrasonic delay line therefore consists essentially of two energy converting transducers (one at the input for conversion from electrical to mechanical; the other at the output for conversion from mechanical to electrical) separated by a transmission medium along which the acoustic waves propagate. The delay time is the time the acoustic wave requires to travel through the medium from input to output transducer.

ULTRASONIC DELAY LINES

Ultrasonic delay lines are grouped into categories according to the material used for the transmission medium and the type of transducer used for the electro-acoustic energy conversion.

Among the various transmission media are:

1. Mercury - no longer used.
2. Glass or fused quartz blocks in the form of a polygon.
3. Glass or fused quartz in the form of cylindrical rods.
4. Metal blocks (aluminum, magnesium, Ni-Fe alloys) in the form of a polygon.

The main types of energy converting transducers in general use are:

1. Magnetostrictive - whereby the physical dimensions of certain materials change under the influence of a magnetic field.
2. Piezoelectric - the effect whereby certain materials change dimensions when subjected to an applied voltage.
3. Optical - whereby the optical characteristics of certain types of glass change as a result of applied stress.

By far the most common combination in the industry today uses metallic wire and/or tape with magnetostrictive transducers. The following discussion will deal primarily with these types which are commonly called magnetostrictive delay lines.

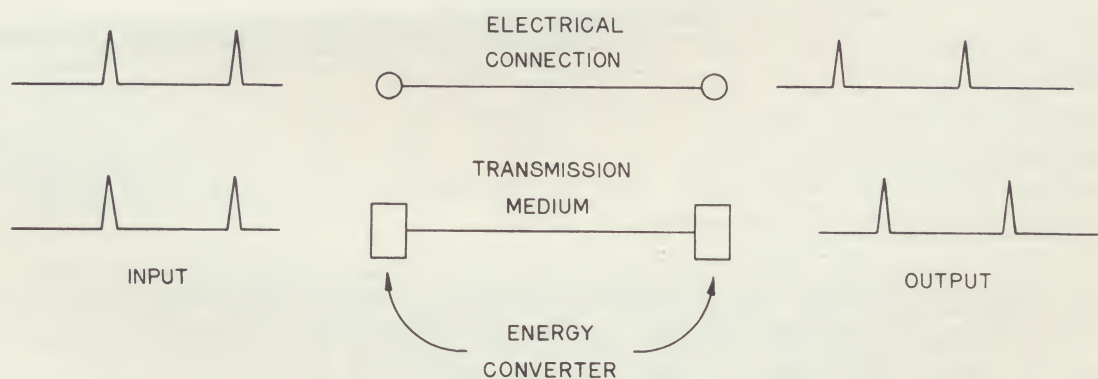


FIG. 1

At this point in the discussion the more serious reader may want to explore the more theoretical aspects of delay lines. A detailed analysis of the delay line as a transmission line is included later. For a good working knowledge of the delay line art it is only required that the reader accept the basic premise that regardless of the application transmission line principles apply, and the performance of the line depends on such parameters as bandwidth, phase and amplitude distortion, effects of temperature on speed of propagation and on line efficiency.

In a well-designed line these parameters are optimized to suit the application. Through strict control over design and production processes, nearly perfect lines can be produced. The following description of manufacturing techniques is greatly simplified in the interest of clarity. It is offered only to acquaint the reader with some of the problems involved in the production of high-performance magnetostrictive delay lines.

HOW ARE MAGNETOSTRICTIVE DELAY LINES CONSTRUCTED?

1. A delay line may be constructed by placing two coils around a piece of magnetostrictive material and biasing each of the coils with a small permanent magnet. The delay line made in this fashion is said to operate in the longitudinal mode, because the nature of the stress pattern induced in the material is "push-pull" along the axis of the medium. Compressions and expansions in the material travel down the medium in exactly the same manner that sound waves propagate outward from a loudspeaker.

A pulse induced in the input coil (or transducer) causes a stress wave to propagate outward in both directions along the magnetostrictive wire. The pulse traveling toward the left in Fig. 2 is absorbed in a soft, rubbery termination known as a damping pad, while the one traveling toward the right reaches the output coil in a few microseconds later and induces an output pulse by the inverse magnetostrictive effect. The stress pulse continues on, somewhat diminished in power to the output damping pad where it is absorbed.

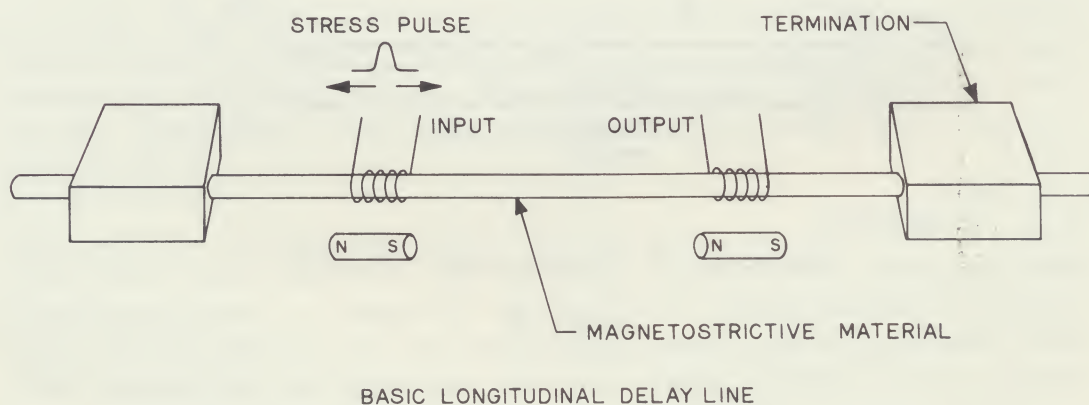


FIG. 2

The speed of acoustic signals in a metallic wire is approximately five microseconds per inch of material. Variations in delay can be easily arranged by mounting one or more transducers on a lead screw, and changing their position with respect to the linear dimension of the delay medium.

In practice, 50 microseconds (about 15" including hardware) of delay is the most that is recommended for the longitudinal delay line. Lines longer than this length become somewhat unwieldy in size for modern packaging techniques. Various distortion effects, peculiar to the longitudinal mode of operation, also combine to cause poor signals in delays much longer than 50 microseconds.

2. Torsional Delay Lines

The torsional delay line, an improvement upon the basic longitudinal line, removes many of the restrictions inherent in longitudinal operation.

Consider a longitudinal line fabricated out of metallic tapes rather than wire. Two input transducers are used, arranged in opposite polarity such that the top tape is "pushed" when the bottom tape is "pulled".

If these tapes are now welded to a wire that is somewhat thicker than the tapes, they form a "hinge" or mode converting junction. Longitudinal motion is converted to torsional motion by the junction, as illustrated in Fig. 3.

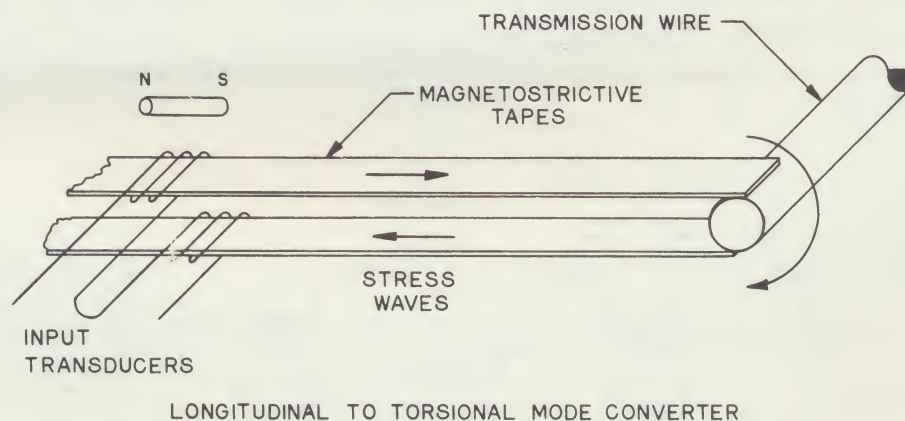


FIG.3

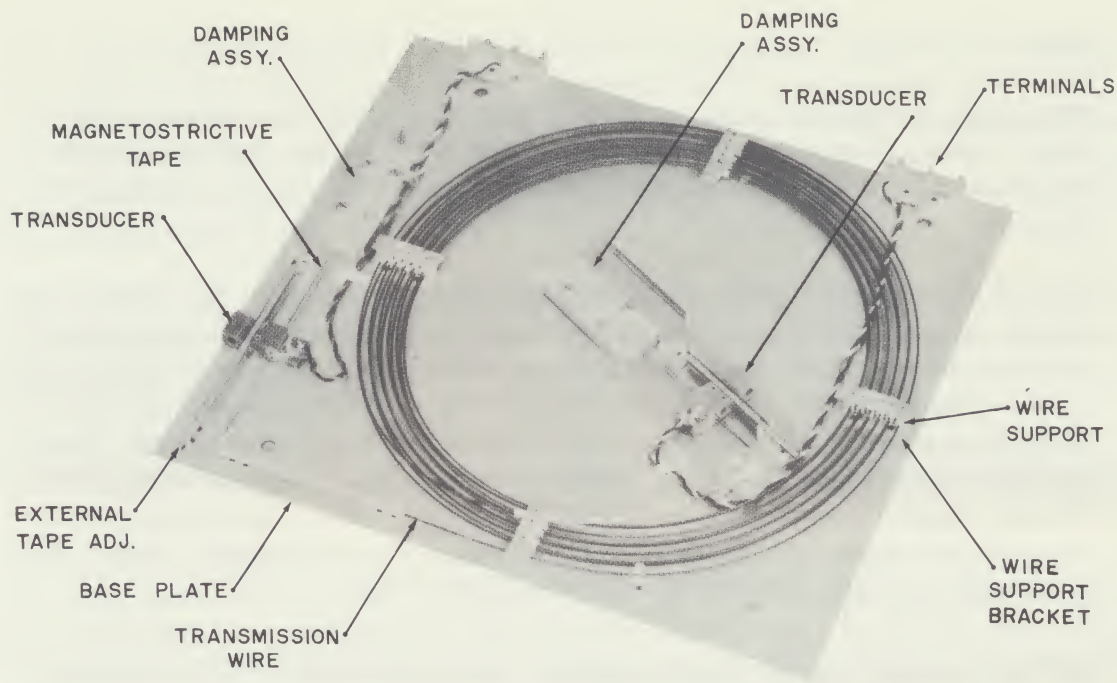


Fig. 4 -- Typical Digital Devices magnetostrictive delay line equipped with removable hermetically-sealed cover. Ruggedized construction permits reliable operation under severe environmental conditions.

After the longitudinal stress pulse is converted to rotational motion, it travels down the cylindrical medium in a helical path. Forward velocity is slowed even further, approximately to half the velocity of the longitudinal case. Coefficients of 9 microseconds per inch are achieved in this mode.

Distortion of signals in long longitudinal lines prevents large amounts of storage capacity in that mode. Similar effects are present in torsional lines, but to a much smaller degree. The torsional medium may, in fact, be coiled into a spiral or helix for greater packing density without adversely affecting performance.

A second mode converting junction is used near the output delay area in order to convert back to longitudinal operation, before generating the electrical output. The reversion is performed in order to take advantage of the high magnetostrictive efficiency of longitudinal tapes.

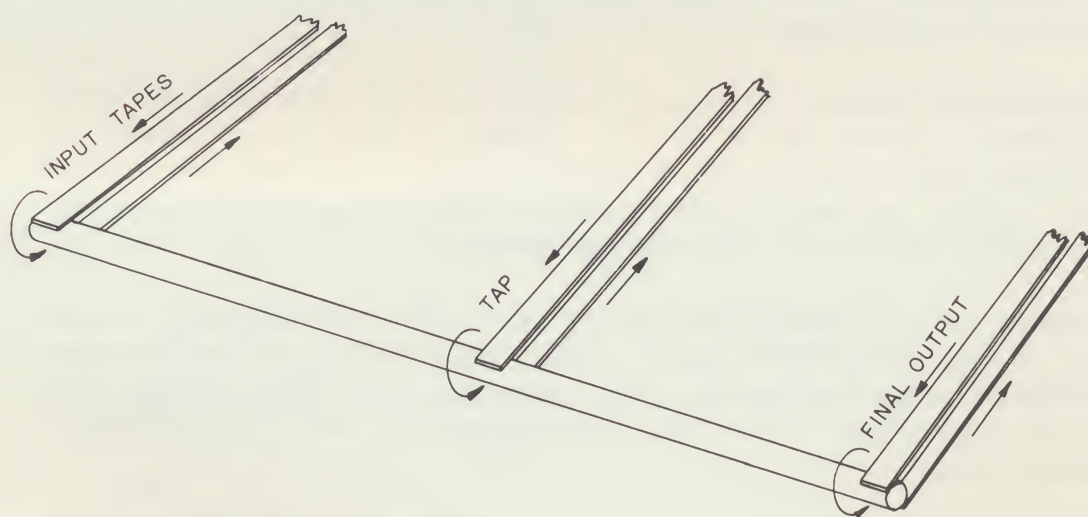
One obvious conclusion which can be drawn at this point is that there is no requirement for the torsional transmission material to be magnetostrictive. A material with a good magnetostrictive coefficient may be chosen for the longitudinal tapes, while a material with good acoustical transmission characteristics would be the proper choice for the torsional medium. Fig. 4 shows a typical configuration for a spiral-shaped torsional delay line using longitudinal transducers.

3. Taps

Many logic schemes can be greatly simplified by the use of tapped delay lines. Generally, however, each type of tap limits the performance of the delay line in a manner peculiar to the method employed.

Longitudinal delay lines are well suited for tapping. An additional output transducer, situated at any point between the input and final output transducers, will produce an output at a delay proportional to its distance from the input transducer. Amplitudes will fall off proportionately with distance from the input transducer, but these may be compensated for by suitable termination. A longitudinal line may be tapped as often as every two microseconds, subject to mechanical limitations, and special techniques are necessary when the first tap is within five microseconds of the input.

Torsional delay lines can be tapped, but only under special conditions. The most straightforward way of achieving such a tap is to weld an extra set of longitudinal tapes at the required point along the torsional delay medium. (See illustration in Fig. 5.) These tapes are then brought out to a convenient spot in the center of the assembly, and a transducer and damping block attached. What must be realized with this type of tap is that the intermediate weld for the tap introduces a discontinuity in the acoustic conducting medium,



METHOD OF OBTAINING TAPS ON TORSIONAL LINE

FIG. 5

and that reflections are generated at this point. Halving of the overall signal to noise ratio of a corresponding untapped delay line is not uncommon. When "good" signal to noise ratios are still required it is recommended that two separate lines be driven in parallel. Energy lost in the damping pad associated with the tap introduces an additional 3 db. loss.

When the tap is within a few microseconds of either the input or the output, it is possible to mount a receiving transducer directly on the input or output tapes. No sacrifice of signal to noise ratio is made under these conditions.

There is one other means of tapping magnetostrictive delay lines which relies upon direct detection of the torsional stress pulse. In order to achieve this type of tap, a cylindrical field, concentric with the long axis of the torsional delay medium must be set up. A direct current, passed through the delay wire, will generate the proper vector field. Acoustic input to this type of delay line is the same as for an ordinary torsional line - longitudinal input tapes, transducer and damping pads. Outputs are generated with transducers which consist of single coils wound around the torsional medium.

The Wiedemann effect, as the technique of torsional tapping is known, is a very inefficient means of recovering acoustic energy. Output amplitudes are much lower than corresponding torsional lines, but this effect permits large numbers of taps (one hundred tap lines have been constructed) to be used on a single line while maintaining output amplitudes at later taps. At present, the Wiedemann line is suitable only for laboratory environments, because the delay medium cannot be held fixed with respect to the output transducers under shock and vibration (a firm support on the delay wire will absorb most of the signal) and delay will thus shift under a sharp blow. These lines do find use in correlators where a customer is willing to set exact tap positions by sliding the transducers along the wire to the proper spot before using the device.

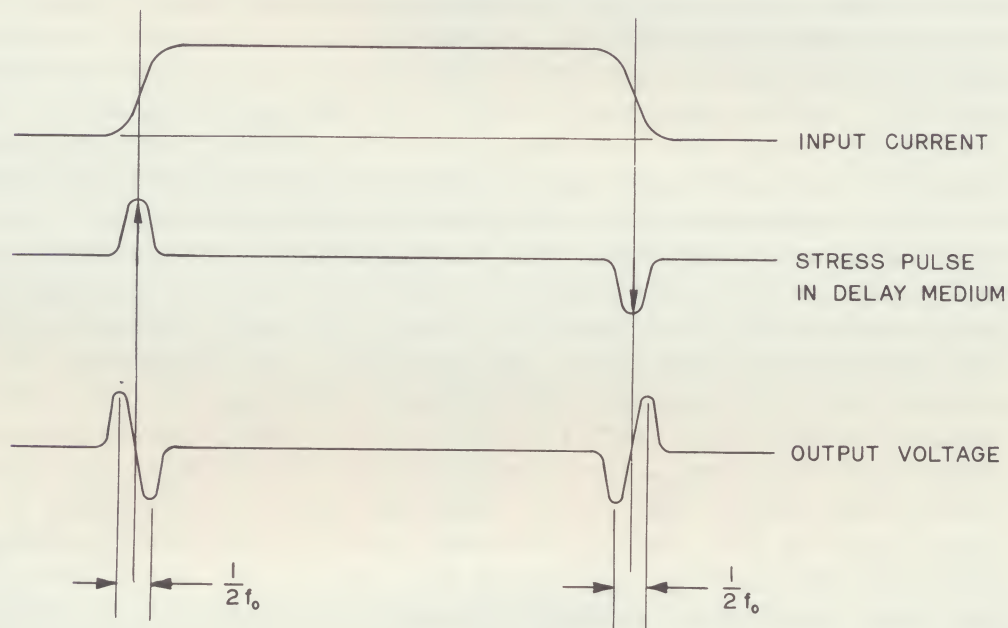
HOW ARE DELAY LINES USED?

1. Recording Techniques

The magnetostrictive effect is current-generated and follows the derivative law common to magnetic phenomena. Since both input and output are magnetostrictive processes, the output of a delay line is the double derivative of the input current waveform. The response to an input current step is shown in Fig. 6.

In a practical, frequency-limited system, the rise and fall times become finite and the distance between the two halves of each doublet translates into the system "resolution".

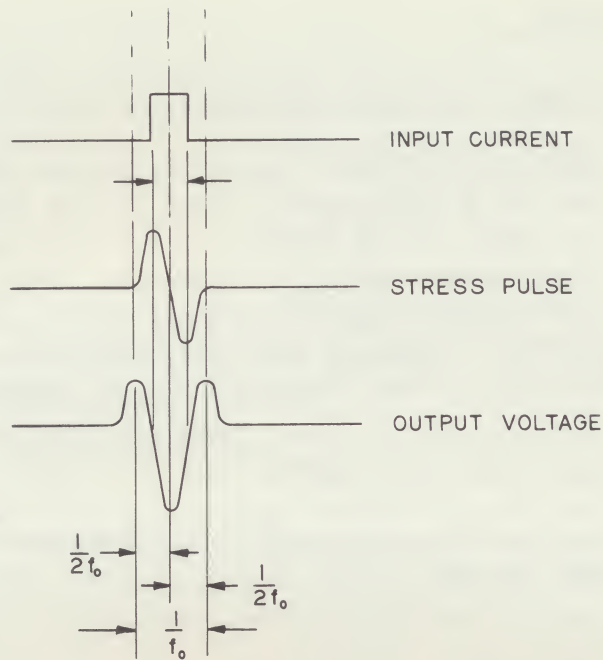
Resolution, for the moment, is defined as $1/2 f_0$. The reason for this will become apparent shortly.



DELAY LINE RESPONSE TO CURRENT STEP

FIG. 6

Consider, now, the effect of shortening the input pulse width. As this width is decreased, the output doublets corresponding to each edge of the input pulse will be observed to merge. The limiting condition on this parameter would be the case where each individual doublet can no longer be detected as an entity - where the second cannot be distinguished from the first. If the two negative peaks merge, the triplet thus generated still indicates that it is composed of two doublets, and the individual pulses have not lost their identities:



DELAY LINE RESPONSE TO CURRENT PULSE OF FINITE WIDTH

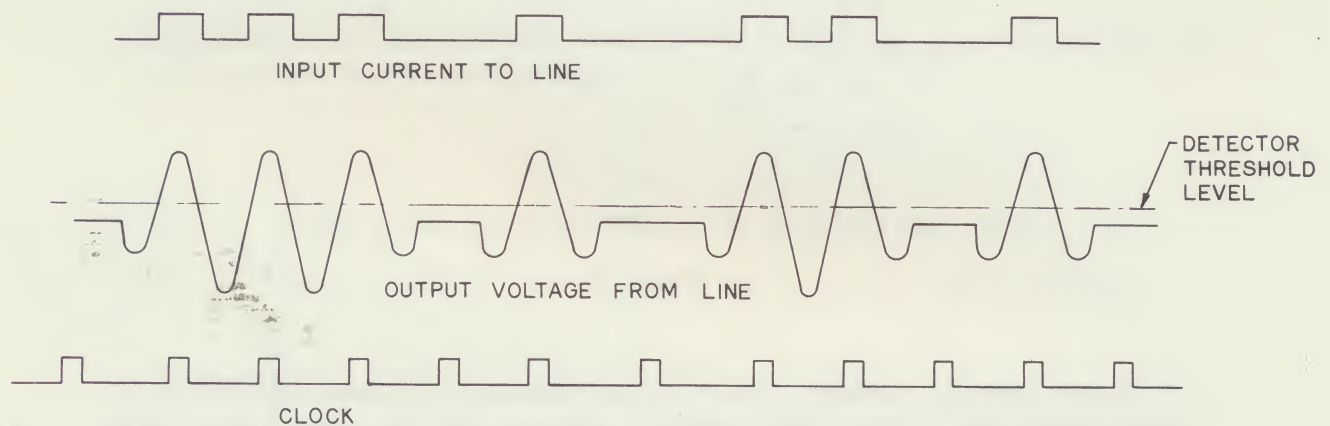
FIG. 7

Similarly, if the polarity of the input pulse is reversed then the output polarity will also be reversed. Note that no delay has been shown between input and output pulses for purposes of clarity. This gives the false impression that an output occurs before the start of the input. The above waveforms form the basis of all digital recording techniques.

RECORDING TECHNIQUES

1. Standard Return to Zero Method of Recording

The most straightforward method of recording digital information is to represent a "one" by a pulse and a "zero" by no pulse. This is called the return to "zero" or RZ method because the current returns to zero between successive bits of information. The maximum bit rate at which the delay line should be used in order to provide adequate operating margins is equal to the bandwidth of the line, which is also the value of the center frequency f_0 for properly designed delay lines.



TYPICAL R.Z. MODE WAVEFORMS

FIG. 8

This corresponds to a minimum spacing between bits of $\frac{1}{f_0}$. The width of the input pulses should not exceed $\frac{.5}{f_0}$, and in general $\frac{.4}{f_0}$ will yield greater operating tolerances.

A typical input pattern for standard RZ recording is shown in Fig. 8, together with the output waveform from the delay line. No time delay is depicted for the purpose of clarity.

If the delay line is being used for storage purposes, it is necessary to amplify the line output and restandardize it for both time and amplitude before recirculation. Amplification is conventional, the only requirement being to provide sufficient signal to drive the re-timing gate. Several methods are available for re-timing, the choice depending mainly on the ease with which delay temperature characteristics of the line can be obtained. If the delay line can readily be made to have a delay drift of less than ± 0.1 bit over the required temperature range, then the simplest and most economical method of

re-timing is to "AND" the output of the linear amplifier with a strobe clock having a pulse duration in the order of 0.2 bit spacing. In order to prevent noise from operating the "AND" gate, it is necessary to have a threshold bias on the gate equal to about 40% of the amplitude of the amplifier output. The output of the "AND" gate is then readily reshaped suitable for recirculation.

While this RZ method has economic advantages it has several operating limitations, particularly under moderate to severe environmental conditions of temperature and vibration. Because of the fact that the amplitude from a delay line of 2,000 microsecond can change as much as 2:1 over a temperature range of 0--50°C it is apparent that the threshold range for satisfactory operation becomes very limited. Also, any spurious pulses induced in the line due to shock and vibration or even system noise that exceeds the threshold value will cause errors. The combined effect of these two factors can reduce the dynamic signal to noise ratio of the system from a value of 10:1 under lab conditions to less than 2:1 under typical service environments.

2. Non-Return to Zero Method of Recording

When the individual writing current pulses are spread out in time so that they occupy a full bit time the recording technique is called "Non Return to Zero" or NRZ.

The reason for the name is that the pulses lose their individuality, and the writing current does not return to zero between successive "0"s or successive "1"s. Instead the direction of current reverses when a "1" follows an "0", or when an "0" follows a "1".

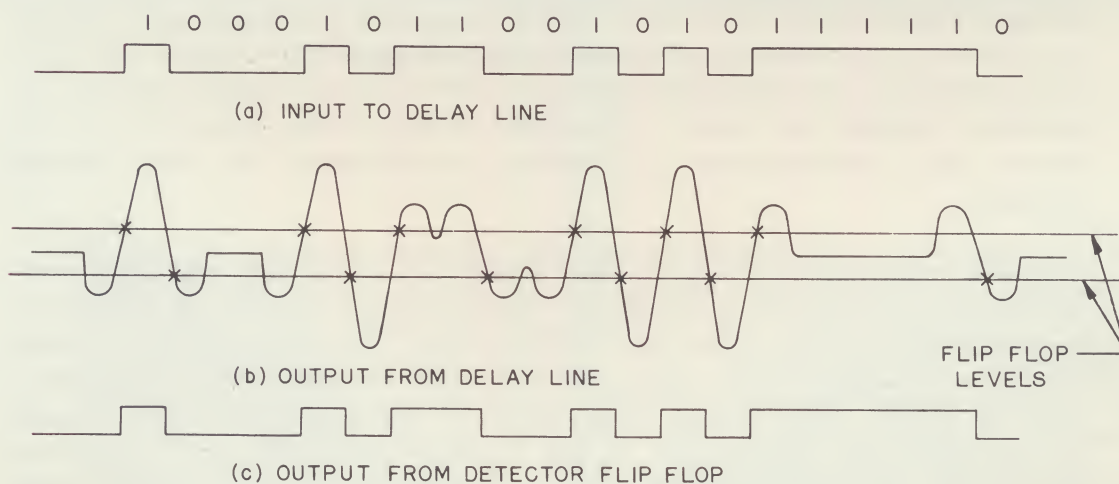
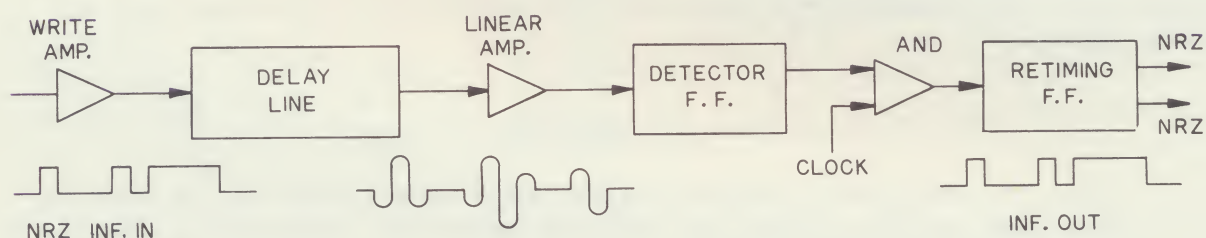


FIG.9

If this method is employed for storage purposes then for a line having a center frequency and bandwidth f_0 it is possible to operate at a bit rate of $2 f_0$. Thus for a given line it is possible to store twice as much information by using NRZ mode than by using RZ mode. This is apparent from the fact that in NRZ mode a single edge of current represents a bit, whereas in RZ mode two edges are required per bit.

Typical waveforms for NRZ recording are shown in Fig. 9.

It will be noticed that there is a difference in output voltage depending on the information pattern. Where the combination 010, or 101 occurs the two dipulses superpose to produce a double amplitude pulse. Several different schemes have been used for detecting and reshaping the output waveform, the simplest being that indicated in Fig. 10.



NRZ RECORDING BLOCK DIAGRAM

FIG. 10

The output of a linear read amplifier feeds a flip flop which can be set and reset by positive and negative pulses in excess of a certain threshold level. The flip flop will then change state when the input to it exceeds the threshold different from the one which caused the previous change of state. No retiming has taken place up to this stage and it is necessary to provide an additional flip flop for this purpose.

The NRZ mode of recording is very attractive where the maximum possible storage capacity is required and provides this at the additional expense of one flip flop over the RZ mode. It has somewhat lower operating margins under moderate to severe environmental conditions than RZ mode. This comes about because the maximum noise present in the output is appropriate to the double amplitude from the 010 or 101 pattern, while the detector flip flop must still recognize the single dipulse.

3. Phase Reversal Mode of Recording

The phase reversal mode is a modification of the standard RZ mode, information being written into the delay line in the form of a positive pulse to represent a "one" and a negative pulse to represent a "zero" or vice versa. The maximum bitrate is the same as for RZ, that is, f_0 .

Typical waveforms are shown in Fig. 11.

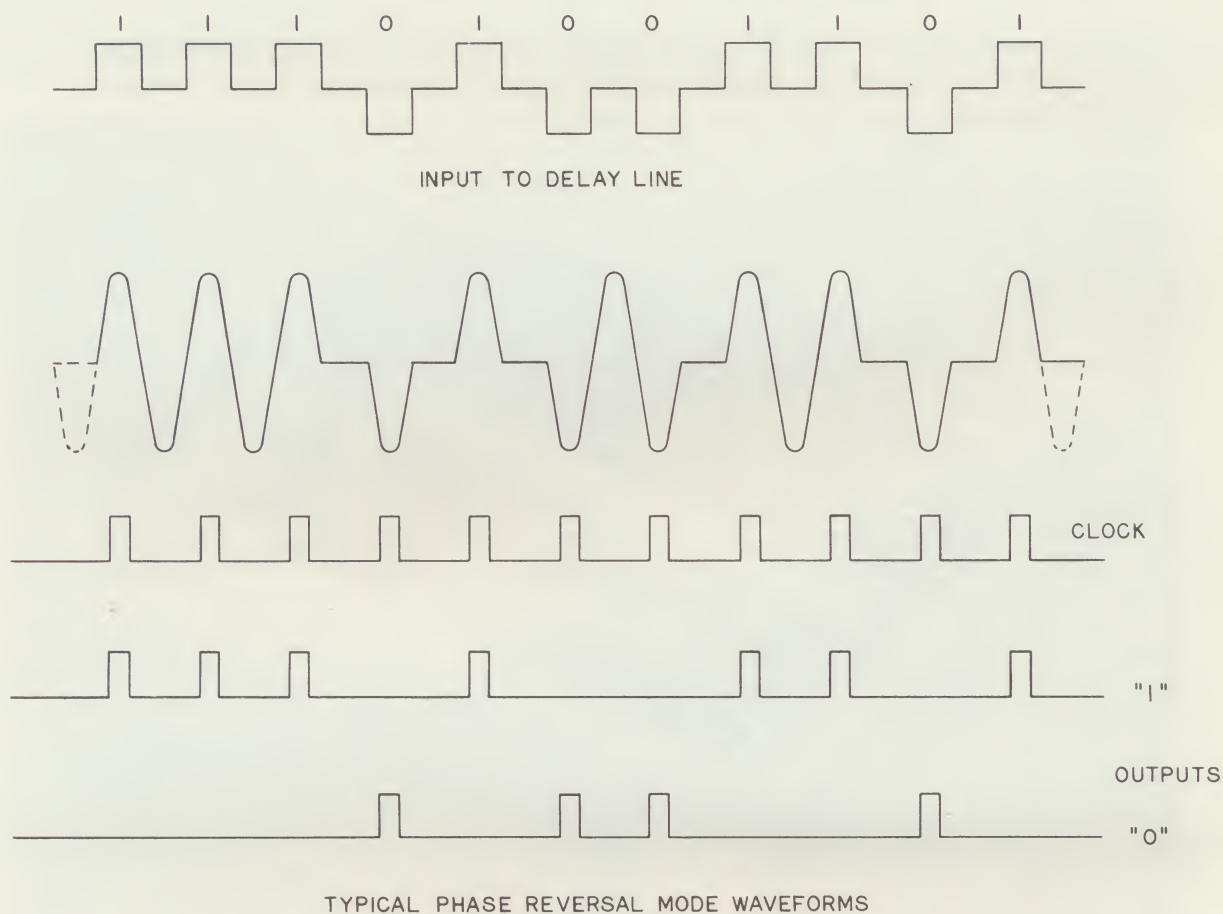
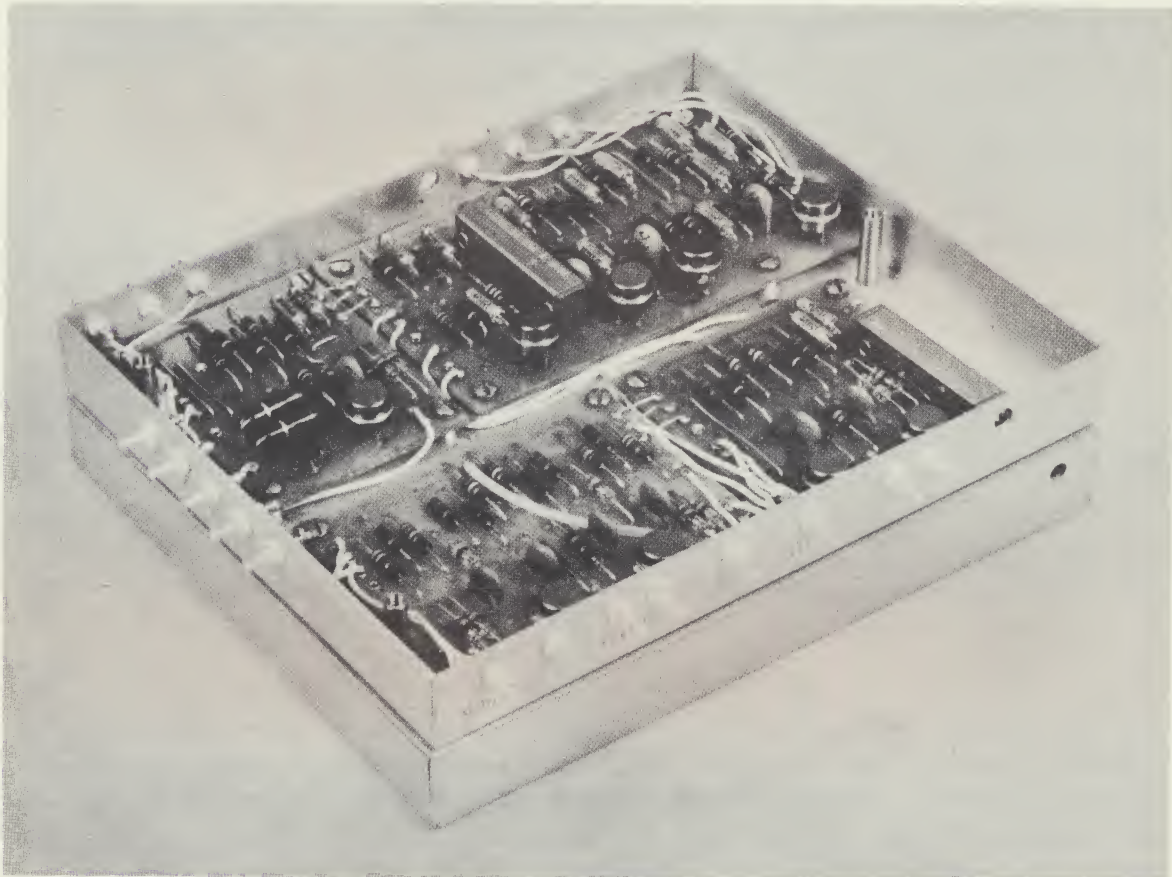


FIG.11

There are several important points to notice about this mode of recording. Because information is always represented by a pulse both for "ones" and "zeros" the requirement of a finite threshold level as in RZ and NRZ no longer applies. It is necessary only to determine whether the output from the line is positive or negative at clock times, in order to recover the information. This is readily accomplished by "Anding" the read amplifier output with Clock. The Phase Reversal mode gives far greater protection against noise and amplitude-temperature variations than either the RZ or NRZ mode. This derives from

the fact that the amplitude of either the positive or negative output pulses must be reduced almost to zero before the "AND" gate detector introduces errors.

This mode is definitely preferred where the bit rate and storage capacity requirements are satisfied by RZ recording and it is almost essential where operation under conditions of shock and vibration, or over wide temperature range is required.



Complete DDI memory system including electronics (see Fig. 10) occupies less than 25 cubic inches and consumes approximately 3 watts of power.

FACTORS AFFECTING DELAY LINE OPERATION

1. Noise

Aside from the shielding problems inherent with millivolt-output devices, delay lines exhibit specific noise characteristics which must be considered if the devices are to operate to their full capability. Input-output feedthrough, reflections, waveform distortion and acoustic noise are the specific factors which combine to make up overall pattern noise and which determine the system detection margins.

Inputs in the tens-of-volts region and outputs in the tens-of-millivolts region combine to make delay lines sensitive to direct feedthrough. Delay lines themselves are designed such that feedthrough is well below 20:1 on a single pulse basis. Care must be taken, however, that cabling to and from the delay line does not worsen this characteristic. In general, standard techniques of careful layout are quite adequate to cope with the situation.

Reflections from the mode-converting junctions become apparent in torsional delay lines below 500 microseconds in length. Energy reflected from each of the two welds creates a "third-time-around reflection" which appears at three times the total delay of the line. Ratios of 20:1 on this parameter are easy to achieve by special techniques, and it is only in lines below 100 microseconds that a reduction in performance is sometimes necessary.

Waveform distortion is perhaps the most important of the noise problems of any dynamic device of this type. The problem must be attacked from both a vendor and customer point of view, as any complete solution depends on both parties cooperating closely toward establishing specific testing techniques.

The response of a delay line to a pulse input has been shown to be a triplet. Four triplets are shown in Fig. 12, the first of which would be obtained from an ideal delay line.



OUTPUT WAVEFORMS INDICATING TYPICAL FAULTS

FIG.12

The second triplet results from a line which is improperly matched to its circuitry, and thus exhibits a pulse "ring". Proper termination with resistive and capacitive components will eliminate this effect. The third and fourth triplets exhibit various types of dispersion in which the frequency components arrive out of their proper phase relationship.

These various types of noise, under pattern conditions, create baseline variations which could cause false triggering, if the triggering level is set low enough to be activated by these peaks. The noise has a specific relationship to the triplet, and will both add to other noise and subtract from available signal depending on the pattern being recirculated through the delay line. The trigger level is properly set midway between the smallest true output signal and the highest noise peak in order to achieve the widest safety margin on detection.

Noise can be specified either on a static (single-pulse) basis or under pattern conditions. Since waveform distortions of the type exhibited in the second dipulse are a strong function of the drive and read amplifiers, meaningful testing is best achieved using the electronic circuits with which the line will be used. The user should designate the impedance he will offer to the delay line. During final tests a conscientious manufacturer will place these load terminations on the delay line and any additional terminations which may be required to optimize performance will be placed inside the delay line.

Should no terminations be specified, the manufacturer will recommend proper values. It is important that these recommendations be followed for best results.

Pattern tests, which are really the ultimate test of the safety margins of a line are best performed using the final read and write amplifiers. Generally, static (single-pulse) tests will suffice for initial work, although in critical applications, pattern tests should be specified as soon as enough characteristics are known.

The pattern test becomes mandatory for production requirements if "best performance" is desired. It is recommended that, for these tests, an operating production model of the circuitry be supplied by the customer to manufacturer so that he may "tune" the lines directly to the associated circuitry.

Static ratios of 20:1 (26db) are typical of RZ lines in most environments, although very high or very low frequency lines will sometimes require a reduction in this specification. NRZ lines, which may be considered as "half-triplets" have half the amplitude of the corresponding RZ line, but exhibit the same noise characteristics. These lines respond typically between 10 and 20:1 on single-pulse tests. Corresponding dynamic ratios run between 5:1 and 8:1 although 10:1 can be achieved in certain cases.

The figures of 10:1 and 20:1 do not represent the entire baseline response of a delay line. As indicated in Fig. 13 this represents a single peak within two microseconds of the output pulse. Generally the associated baseline in a static measurement will have its highest peaks between 20:1 and 40:1, and better figures are possible. A typical static response is:

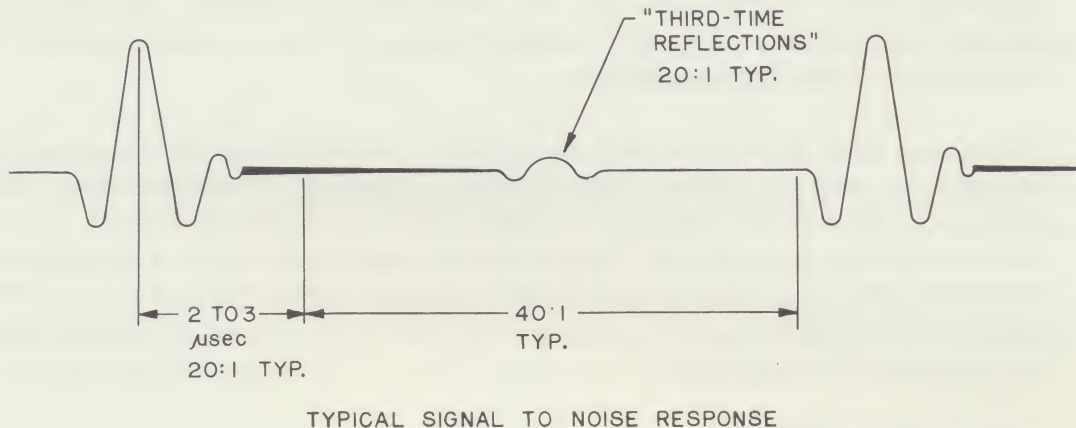


FIG.13

The only exception to this discussion, as shown above, is that the "third-time-reflection" on lines shorter than 500 microseconds will generally be 20:1 instead of 40:1.

2. Input Characteristics

Because a delay line is a current-operated device, it is best driven from a constant-current source which can provide reasonably fast (100 nsec for 1 mc work) rise and fall times into a resistive load. In practice, source impedance of 200 to 1000 ohm are typical, and these values are quite within reason. The important point here is that the output level of a delay line will depend on both the input current and the number of turns permitted on the input transducer. As the driving impedance is increased, more and more turns are permitted on the input transducer.

The obvious conclusion from this discussion is that the driver should operate from the highest transistor-supply voltage available to the customer if he is to simplify the gain requirements on the read amplifier. Reducing the source impedance from a low voltage source is not sufficient because lower impedance transducers would then have to be used.

A good rule of thumb for RZ work is that the input pulse width be $0.4/f_0$ where f_0 is the maximum pulse repetitive frequency. Delay lines will operate up to $0.5/f_0$ (the theoretical maximum) but lines above a few milliseconds in length suffer some pulse spreading and sometimes do well with a small "cushion".

Damping pads, used in both longitudinal and torsional delay lines, lose much of their effectiveness below 500 kc, and the resulting line exhibits baseline noise far in excess of what it would exhibit at 1 mc. Dispersion effects, shown in Fig. 9, contribute greatly to waveform distortion at low frequencies. If a high-performance line is desired at an operating frequency between 100 kc and 500 kc, the easiest way to obtain this is simply to reduce the duty cycle of the input pulse, narrowing it to a value in the 1.0 microsecond region. As far as the line is concerned, it is then operating at 500 kc, even though that rate is not being approached.

Extending this argument slightly further, systems nominally operating at 100 kc can be made to have dynamic signal to noise ratios which approach their static signal to noise ratios. If the technique of duty cycle reduction is applied here, the maximum information loading presented to the line is a one microsecond pulse every ten microseconds. Main pulse noise has less chance to "add up" and so dynamic noise is significantly reduced.

3. Output Characteristics

Delay line output amplitudes vary from one to fifty millivolts depending on delay, center frequency and input current. Outputs are proportional to inputs within close limits.

Read amplifier input impedance should be chosen with the understanding that low impedances will cause "detuning" of the output transducer and limit the bandpass characteristic of the delay line. While lower read amplifier input impedance generally results in higher first-stage gains, it also limits the output amplitude of the delay line so that no real improvement is obtained.

An input impedance level of 3.3K is typical although greater values are occasionally recommended for high-frequency lines.

Problems with poor resolution on delay lines may often be traced to an attempt to use an amplifier with a lower input impedance than that for which the delay line was designed. In some cases users have been known incorrectly to assume that both a resistive termination and an amplifier input impedance of the recommended value are required which is equivalent to a load impedance of half the recommended value.

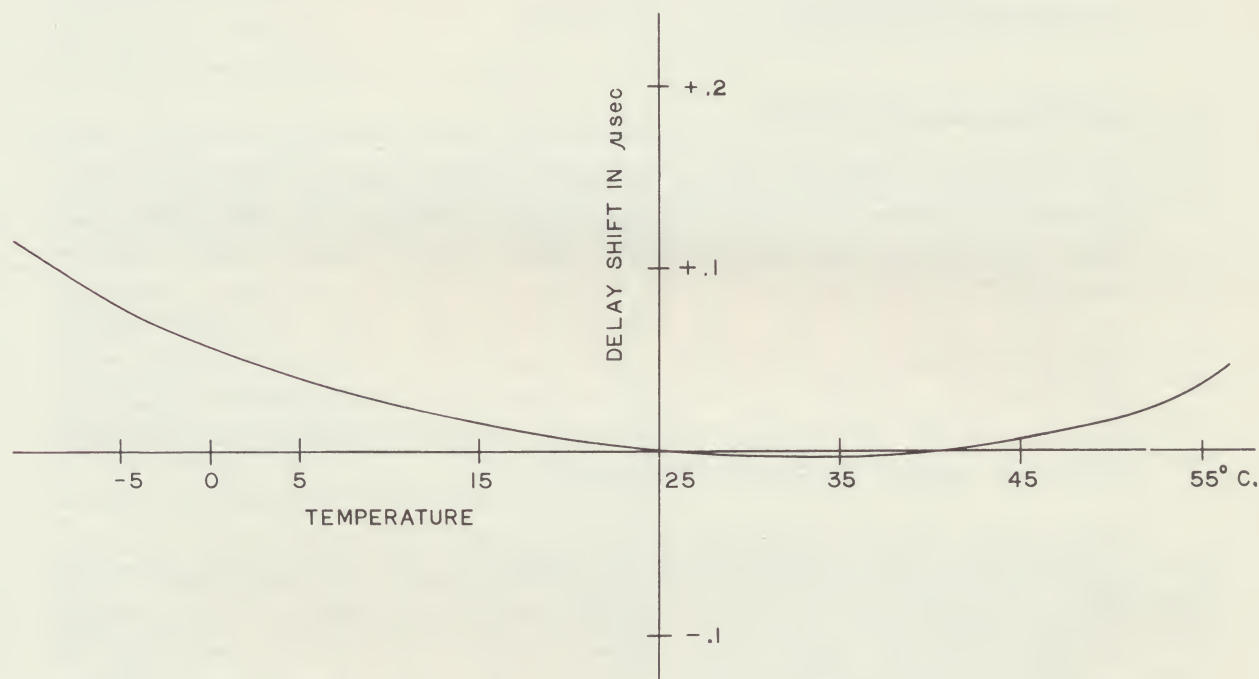
Trim adjustments on final delay are normally provided on delay lines of this type. An adjustment of ± 4 microseconds is typical; more can be provided if necessary in the larger packages. If the delay lines are required to operate during shock and vibration, it is sometimes necessary to restrict this delay adjustment because it constitutes a noise source. If operating shock and vibration specifications are expected, a minimum range of adjustment should be used.

4. Temperature Coefficient

All metallic alloys exhibit the familiar phenomenon of expansion in both linear and transverse dimensions under increases in temperature. Since the delay of a magnetostrictive delay line is a function of the length of the conducting medium, some change in delay with temperature is to be expected.

Longitudinal delay lines are made of materials which must be highly magnetostrictive in nature. The requirement of high magnetostrictive coefficient and sufficient hardness to pass sonic pulses in the megacycle region is not completely compatible with low coefficients of expansion. This problem is one more reason why long longitudinal delay lines do not offer the best performance characteristics. Torsional delay lines offer the further advantage that the torsional material need not be highly magnetostrictive, and choices may be made in the selection of this material to compensate for the high temperature coefficient of the longitudinal material.

Longitudinal delay material exhibits temperature coefficients which are roughly linear in nature, varying from 30 parts per million per degree centigrade to 150 ppm/°C depending on the material. Long, torsional delay lines can be compensated with slightly negative material so that the overall coefficient is reduced to 0.5 ppm/°C or less. These long lines exhibit delay vs. temperature curves which



TYPICAL DELAY TEMPERATURE CHARACTERISTIC
FOR 2000 μsec . D.L.

FIG. 14

are parabolic in nature and, for this and other reasons, it becomes essential to specify the allowable temperature drift in terms of a total number of microseconds over a specific temperature range rather than PPM/ $^{\circ}\text{C}$.

The base point of the parabola is normally positioned in the temperature range of 25 to 35 $^{\circ}\text{C}$ (although it may be positioned anywhere between -30 and +65 $^{\circ}\text{C}$ under special conditions). A slow variation of delay with temperature exists in the region of 5 $^{\circ}$ to 45 $^{\circ}\text{C}$, but extension beyond these limits of temperature brings much more rapid shifts as the steeper part of the curve is approached. The steepness of curve is a function of mean package diameter, the slope increasing inversely with package size. Lines with difficult temperature coefficients are often best packaged in large, pancake boxes for this reason. (See Fig. 13 above.)

Detection methods which utilize constant-level detectors introduce an additional possibility of delay shift with temperature if the output amplitude of the line varies. Over wide temperature ranges of, for example, 0 $^{\circ}\text{C}$ to 60 $^{\circ}\text{C}$ in tight packages, a 2:1 variation in output amplitude may be expected for a line of 2000 usec. Since the rise time of the output doublet (or triplet) may be regarded as a portion of a sine wave, a shift in amplitude amounts to a shift in delay, as the trigger point "moves in time" on the delay line waveform. In these cases, a specific output amplitude level should be specified, and variations in delay measured with respect to this point. Delay shift measurements are otherwise made to either the peak of the waveform or to a zero-crossing.

5. Humidity and Salt Spray

The velocity of propagation of acoustic pulses such as are being discussed is affected to some degree by the "loading" on the delay medium offered by the atmosphere. Short lines (below 1000 microseconds) do not present enough surface for this to become a problem in normal environments, but longer lines may shift in delay during changes in absolute humidity. Air-conditioned environments generally control humidity well enough so that this characteristic need not be considered, but regions where 90% relative humidity is expected generally require protective measures.

Delay lines can be sealed to protect against wide variations in humidity if the requirement calls for this technique. In many cases it is more economical to provide unsealed lines for prototype work in view of short delivery time requirements (thus avoiding the necessity of waiting for special packaging) and to offer sealed lines on a production basis.